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Earth-resistivity Measurements and Interpretations

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EARTH-RESISTIVITY MEASUREMENTS AND INTERPRETATIONS

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BY

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EARTH-RESISTIVITY MEASUREMENTS AND INTERPRETATIONS

This thesis is approved as a creditable, independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree, but without implying that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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INTRODUCTION

The electrical resistivity method of exploring the subsurface of the earth dates back to 1830 and was the result of scientific interest in measurement of self-potentials within the earth (10,17). The first application was made in 1833 when an unsuccessful attempt was made to locate mineral deposits. It was not until 1912 that the method as known today was developed. The first application of this method was made in 1925 when self-potentials of large earth masses were successfully measured. The first commercial application was made in 1927 in an exploration for metallic mineral deposits (10).

During the period between 1912 and the present, the resistivity method has been investigated by a number of persons: Gish and Rooney, Mooney and Wetzel, Wenner, Lee, Tagg, Moore, Heiland, Manhart, and Longacre; to name only a few. In the course of these investigations, the methods of taking the resistivity measurements have been standardized to a large degree, but the manner in which the measurements are interpreted has not been so standardized. Numerous articles have been published describing methods of interpreting resistivity measurements; each of these methods have certain advantages and disadvantages, and no single method can be used successfully to interpret all possible resistivity data.

This thesis is a study of the earth-resistivity method of determining the nature of the earth's subsurface, and is concerned with the method of taking resistivity measurements, several methods of interpretation, and a discussion of the merits of each of these methods.

During the study of resistivity interpretations, a method was devised by the author which allows a direct interpretation of the resistivity measurements from a linear plot of the field data. This study also discusses the application of this method of interpretation, as well as its limitations.

The summer months (June, July and August) of 1962 were spent by the author in taking and interpreting resistivity measurements while employed jointly by the South Dakota State Highway Commission and the South Dakota State Geological Survey. This employment provided an opportunity to gain first-hand experience in the methods of obtaining resistivity data and of the various methods of interpretation and their limitations.

EARTH-RESISTIVITY MEASUREMENTS

In taking earth-resistivity measurements, a current is caused to flow through the earth between two current electrodes which are located at the surface of the earth and act as point sources of current. In order that the electrodes will act as point sources, it is necessary that they penetrate the earth no more than five per cent of the electrode separation (4). The current flow in the earth sets up an electric field, and potential electrodes are used to measure the resulting potential difference between two points on the surface. The resistivity of the earth is a function of the measured potential difference, the current, and the distance between electrodes; and the particular relationship depends on the electrode orientation. The most commonly used electrode configurations are those for which a simple relationship exists. The Wenner configuration of electrode spacing (18) is probably the most widely used (1), and this study will be confined to it and some of its modifications. In the Wenner configuration, the electrodes are located in line and are separated by an equal distance shown as "a" in Figure I (a). The current electrodes are shown as C_1 and C_2, and the potential electrodes as P_1 and P_2.

The typical resistivity instrument measures the potential difference between P_1 and P_2 by comparing it to an internally generated reference voltage by use of a potentiometer and a galvanometer. (This will be discussed in more detail in the material that follows.)

If the earth is assumed to be semi-infinite and electrically homogeneous and isotropic, the equation for the potential at a point on

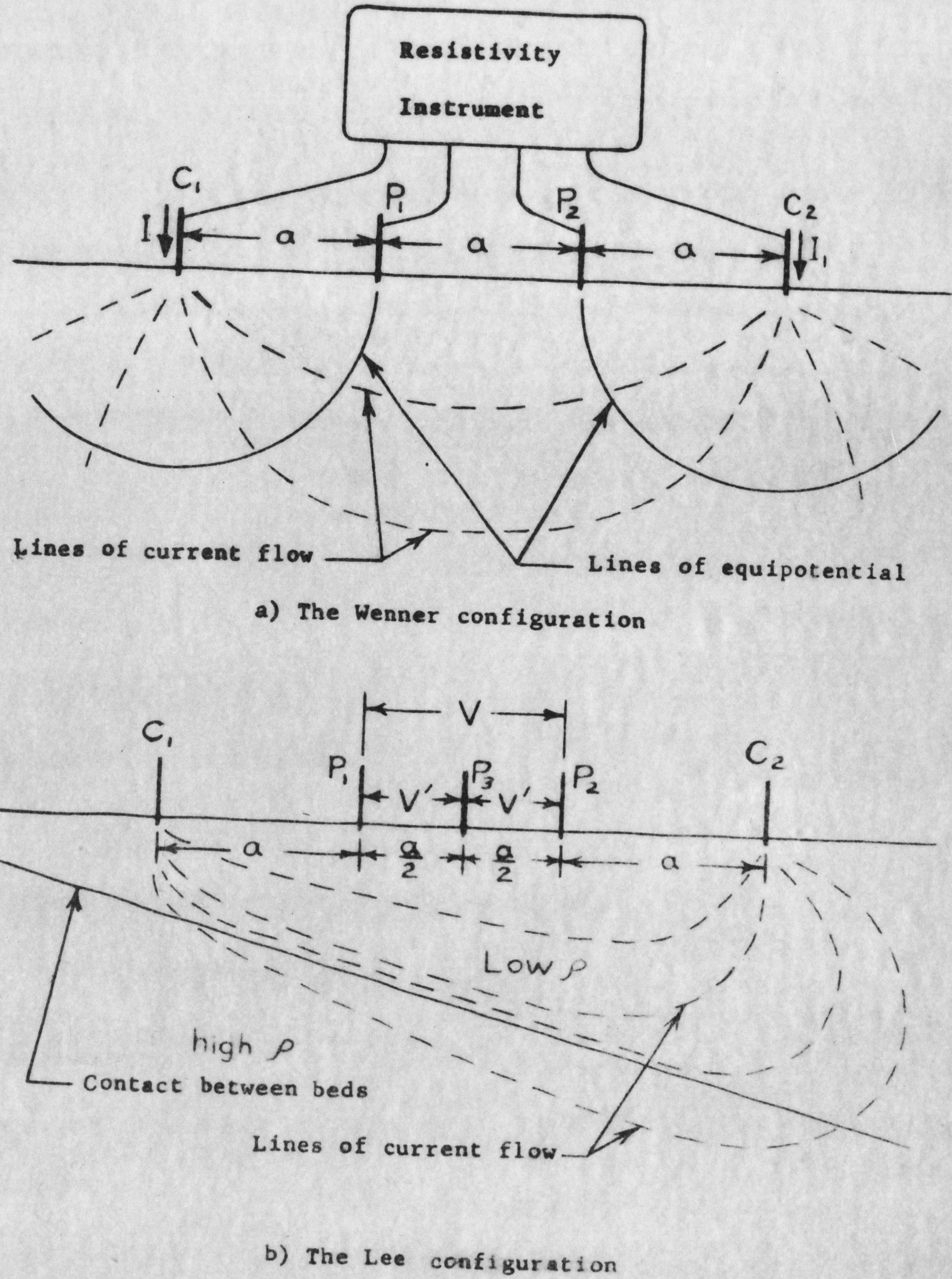

Figure I. Electrode configurations.

the surface of the earth is

$$V = \frac{I\rho}{2\pi r}$$

where V is the potential at any distance (r) from a point source of direct current (I), and ρ is the resistivity of the earth (5,17).

The equation for the potential difference between P_1 and P_2 of the Wenner configuration can be determined from the equation for the potential at a point on the earth's surface. The potential (V_1) at the point P_1 of Figure I (a) (caused by the currents I and I_1) is

$$V_1 = \frac{I\rho}{2\pi a} + \frac{I_1\rho}{2\pi 2a}$$

and because $I_1 = -I$

$$V_1 = \frac{I\rho}{2\pi}\left[\frac{1}{a} - \frac{1}{2a}\right]$$

The potential (V_2) at P_2 is

$$V_2 = \frac{I\rho}{2\pi}\left[\frac{1}{2a} - \frac{1}{a}\right]$$

The potential difference between P_1 and P_2 is

$$V = V_1 - V_2 = \frac{I\rho}{2\pi}\left[\frac{1}{a} - \frac{1}{2a} - \frac{1}{2a} + \frac{1}{a}\right]$$

$$V = \frac{I\rho}{2\pi a}$$

By rearranging the last equation, the resistivity for the Wenner configuration is

$$\rho = 2\pi a \frac{V}{I}$$

The contacts between geologic formations frequently dip (are not horizontal) and cause an asymmetric current distribution in the earth. This is illustrated in Figure I (b). If the upper layer has a lower resistivity than the lower one, as shown, the resistivity measured near C_1 will be greater than that near C_2 because the high resistivity layer will tend to increase the measured value at C_1. The Wenner configuration of electrode spacing will determine the average resistivity or the resistivity at the center of the configuration, but if the resistivity of each half of the configuration could be measured independently, the difference in the measured values could be used to determine any appreciable dip in the contacts between geological formations. It would, however, be necessary to know which layer had the greatest resistivity to determine the direction of the dip. This idea is utilized in the Lee configuration in which a potential electrode (P_3) is located half way between P_1 and P_2 and the instrument measures the potential between P_1 and P_3 and between P_2 and P_3 independently. From Figure I (b), it is apparent that $2V' = V$. If this value ($2V'$) is substituted for V in the equation for the Wenner configuration, the resistivity for the Lee configuration is found to be

$$\rho = 2\pi a \frac{2V'}{I} = 4\pi a \frac{V'}{I}$$

The equations for resistivity were determined by considering direct current theory. However, it is not always possible to apply a direct current and obtain correct values of resistivity because ground currents within the earth influence the readings. The ground currents that affect readings have long periods of oscillation (seconds, minutes or even hours) (3), and during short time intervals, they may be considered as direct current. These currents will add to or subtract from the resistivity instrument current, and the voltage between the potential electrodes is no longer caused by the instrument current alone. The correct value of resistivity can be determined by taking readings with instrument current flowing alternately in opposite directions. The ground current will increase the resistivity reading for one direction of instrument current and will decrease it by an equal amount for the other direction, and the average of the two readings is the correct value for resistivity.

Some resistivity instruments use direct current which is reversed manually and the average of the recorded values of resistivity is taken as the correct value. More commonly, a commutator or vibrator is used to reverse the direction of current. If the frequency of the current reversal is great enough and a galvanometer is used as a current sensor, it will be unable to follow the rapid changes in potential and the instrument will automatically average the resistivity. However, the frequency of the vibrator must be kept low enough so that skin effects (concentration of current at the earth's surface) do not void the readings (17). The frequencies employed in earth-resistivity instruments are generally from 5 to 50 cycles per second (14), but range as high as 400 cycles per second in some special purpose instruments (2).

High frequency ground currents do not affect resistivity measurements because they are generally quite weak (14), and if they do have an appreciable amplitude, they are damped out by the galvanometer inertia. Frequencies on the order of the vibrator frequency are troublesome. When ground currents of these frequencies, and of sufficient amplitude, are encountered, the galvanometer fluctuates at random and cannot be zeroed. Under this condition, the measurements are meaningless. Readings taken near an electric power substation, where 60 cycle ground return currents are prevalent, generally result in erratic readings for resistivity instruments employing a 30 to 50 cycle per second current reversal. However, it is possible to obtain readings by increasing the frequency of current reversal to 400 cycles per second (2).

The manner in which the resistivity instrument measures the potential between P_1 and P_2 is illustrated in Figure II. The voltage E_1 produces the field current (I) flowing through the earth. The resulting potential (V) between P_1 and P_2 is found by adjusting the potentiometer (R) so that no galvanometer current (I_g) flows. By using this method of measuring the potential, the field remains undistorted when the measurement is taken because no current flows in the potential circuit (17).

If the potentiometer is linear and the reference voltage (E_2) is constant, the potentiometer position is a direct function of E_2 and it can be calibrated to read the potential between P_1 and P_2. When a commutator or vibrator is used to alternate the direction of field current, it also reverses the connections to P_1 and P_2, and the polarity of E_2 so that galvanometer current only flows in one direction for a given condition of unbalance. When a commutator or vibrator is used, the field current (I) is essentially direct current and the derived expression for resistivity is valid.

By proper calibration of the potentiometer, the instrument can be made to read resistivity directly in the desired units provided the

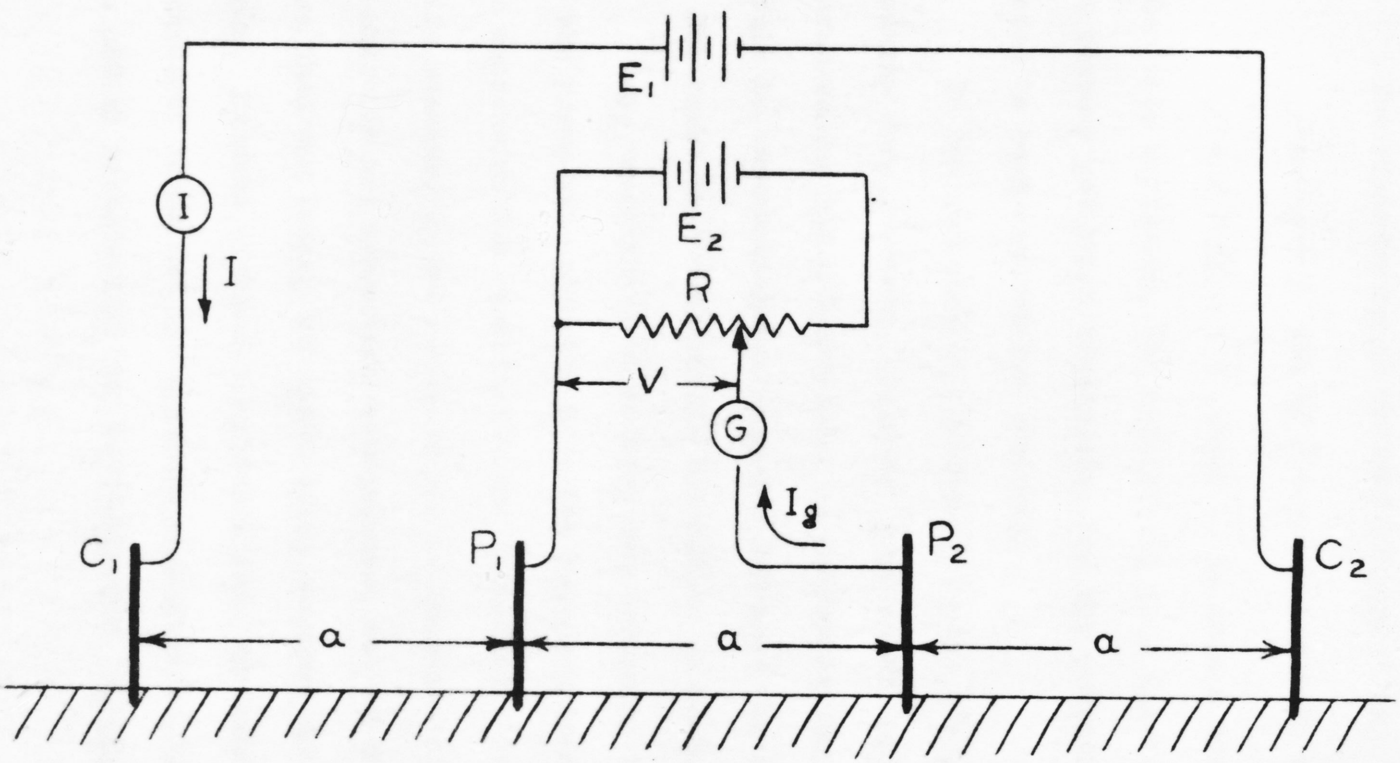

Figure II. Simplified diagram of resistivity instrument.

relationship between the current (I) and the electrode separation (a) remains a constant.

The resistivity as derived on page 5 is

$$\rho = \frac{2\pi a}{I} V \quad \text{and if } \frac{a}{I} = K \text{ (a constant) then}$$

$$\rho = 2\pi KV = K'V \quad \text{where } K' \text{ is also a constant.}$$

Under this condition, the resistivity is a linear function of the voltage between potential electrodes, and the potentiometer can be calibrated to read resistivity directly.

In the resistivity instrument (Model ER-7, Urbana Engineering Products Corp., Urbana, Illinois) used by the author in resistivity measurements, the potentiometer is calibrated to read resistivity directly in ohm-centimeters (ohm-cm) provided the current in milliamperes is set equal to the electrode separation in feet.

Any resistivity instrument can determine the actual resistivity of the earth if - and only if - the boundary conditions used in deriving the expression for resistivity are satisfied. In most cases, the earth being measured is not homogeneous; it consists of several layers, each of which is not completely homogeneous, and if the current flows through more than one layer, the earth being measured is definitely not homogeneous. Because of these considerations, the resistivity measured by the instrument is termed the apparent resistivity (to distinguish it from the actual resistivity) and is designated ρ_a (5,14).

Field Procedure

Resistivity measurements can be taken in two different manners: 1) traversing (resistivity mapping) (5), and 2) depth probing (resistivity sounding) (5).

In traversing, an electrode separation (equal to slightly more than the depth to the layer being investigated) is selected and the measurements are taken at stations along a line. At each station, the resistivity is measured for the preselected electrode spacing. Differences in resistivity readings from one station to another can be used to outline general boundaries between beds of differing resistivity. Such a procedure could be used to outline gravel deposits in till.*

Depth probing involves taking a number of resistivity measurements at one location for different values of electrode separation. Since the separation is a rough indication of the maximum depth which is being measured (4), the maximum separation should be no less than the maximum depth under investigation, and preferrably should be several times as great. A plot of apparent resistivity versus electrode separation can be made from the data obtained, and this "field curve" can be used to predict the various subsurface layers and the contacts between layers. The field curve may be plotted either on log-log or linear graph paper, depending on the method of interpretation used.

When taking resistivity measurements, the location of stations should be chosen with care, and certain areas as described below should be avoided.

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*For definitions of geologic terms, see Appendix A.

Areas of wet ground conditions

Several resistivity measurements were taken by the author in areas of wet ground conditions, and in each case, it was necessary to use the filter on the resistivity instrument (its purpose is to eliminate electrical disturbances due to ground currents, etc.); but even when using the filter, the readings were extremely erratic and were considered to be useless. At times, the galvanometer would fluctuate wildly and randomly over the entire range of the scale. This may have been caused by ground currents, but more probably was the result of poor insulation on the cables connecting the resistivity instrument to the electrodes. Ferret (14) states that fouled insulation on the commutator of the instrument he used caused erratic field current, so it seems logical to assume that current leakage between the cable and the wet earth might cause the erratic readings observed.

Areas containing electrical conductors

Stations near electric power lines, steel post fences, and other electrical conductors should be set up with the line between the electrodes perpendicular to the conductor. If a resistivity station is set up parallel to such a conductor, the field current will find a low-resistance path through the conductor and only a small amount of current will flow through the earth between the electrodes. Under such conditions, the resistivity readings are lowered because of the conductor. This effect is reported by Johnson (6) who states, "the presence of such a conductor (pipe lines or fences with metal posts) is indicated by abnormally low readings which do not change appreciably with an increase in depth or spacing." To avoid such erroneous readings, the resistivity station should be set up with a line connecting the electrodes perpendicular to the conductor, and if it must be set up parallel, the resistivity station should be no nearer the conductor than the maximum electrode separation (and preferrably further). Areas which are likely to have buried pipe or electrical cables should be avoided entirely, if possible, unless the exact location and orientation of the pipe or cable is known.

Range of Resistivities for Various Lithologic Deposits

Interpretation of resistivity measurements is possible because each lithologic deposit has its own characteristic resistivity. The resistivity of one particular deposit may vary from one geographic region to another (17); therefore, any reference for interpretations must be based on the characteristic resistivities of the deposits in the local area under investigation. The reference can be determined by a study of the geologic formations and the use of drill logs (8).

Table 1 shows the range of resistivities for the various deposits along the Big Sioux River in South Dakota. This table was compiled from data taken by the author.

The resistivity ranges shown overlap in many cases; however, the field curve of each deposit has a distinct shape, and the type of deposit can generally be determined from the field curve.

Table 1. Resistivities observed for various deposits

Lithologic Deposit	Range of Resistivities (ohm-cm)
Till	1,000 - 4,000
Outwash with thick alluvium or loess cover	2,000 - 20,000
Outwash with thin cover	10,000 - 50,000
Kames and kame terraces	10,000 - 50,000
Bedrock with shallow overburden	6,000 - 100,000

Outwash with a thick cover of alluvium or loess may lie in the same range of resistivity as till (2,000 to 4,000 ohm-cm), but it is usually easy to distinguish between the two from the field curves. The resistivity of till may vary considerably over short distances because of its composition. In general, till is covered with a shallow layer of organic topsoil that is relatively homogeneous. This topsoil usually has a higher resistivity than the till, depending on the moisture content.

Due to the topsoil, the typical till resistivity curve starts as a smooth curve with resistivity decreasing with depth. When electrode separation approximately equals the depth to till, the curve is in the 1,000 to 4,000 ohm-cm range, and for increasing depth fluctuates in a random manner due to the hetrogeneous nature of till. A typical till curve is shown in Figure III.

Outwash will usually be covered with a layer of topsoil having a much lower resistivity than the sand and gravel beneath. Therefore, the field curve for outwash will begin at a low resistivity (a few thousand ohm-cm) for very close electrode separation. At greater

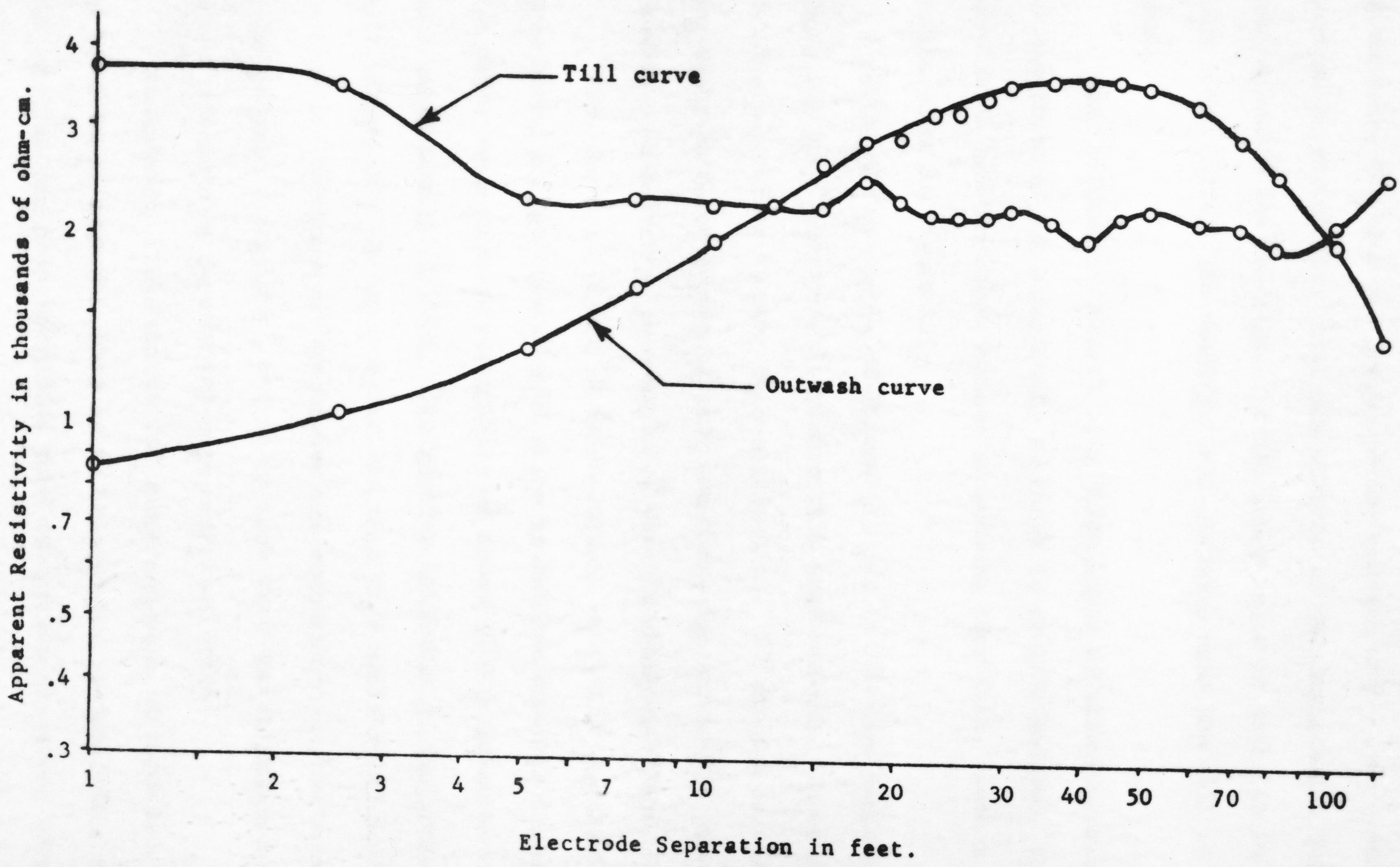

Figure III. Comparison of outwash and till resistivity curves.

separations, the sand and gravel of the outwash will cause a continuing increase in resistivity until the effects of the layer below the outwash influence the readings. If the lower layer is till (as in the Big Sioux River valley) the readings will decrease when the till is encountered.

When outwash is covered by a thick layer of alluvium or loess, the magnitude of the resistivity readings is greatly reduced, but the curve still has the shape typical of outwash over till. Such a curve is also shown in Figure III.

Although the curves of Figure III are in the same resistivity range, the curve shape distinguishes till from outwash. However, it is not always possible to make this distinction. If outwash consists of very silty sand, or layers of sand and clay, the curve will strongly resemble a till curve. An example of this is shown in Figure IV.

Also shown in Figure IV is an outwash over till resistivity curve which has the same general shape as the one shown in Figure III. This curve has a maximum resistivity of about 45,000 ohm-cm at an electrode separation of 55 feet. The greater thickness of the gravel deposit is probably the main reason for this high resistivity reading. The type and thickness of overburden has some effect on the magnitude of the outwash resistivity, but it appears that the thickness and nature of the outwash deposit may have a greater effect.

Resistivity field curves for kames and kame terraces are similar to those of outwash. This is to be expected because kames and kame terraces are also stratified sand and gravel deposits. The major

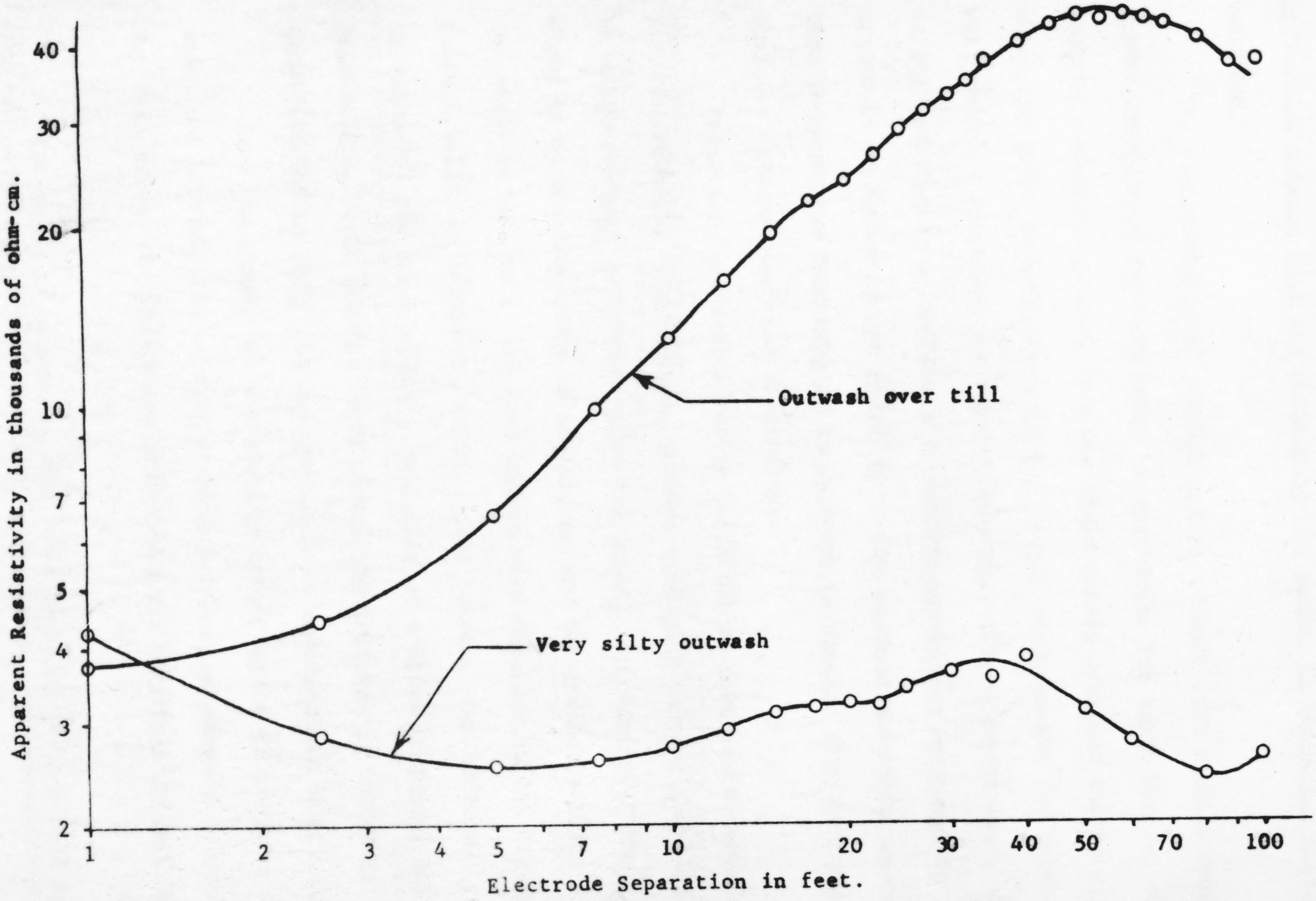

Figure IV. Outwash over till resistivity curves.

difference between them and outwash is the manner in which the deposit occurred.

The resistivities of outwash and of bedrock with shallow overburden are also of the same order of magnitude, but again the two can generally be distinguished from the field curves provided the measurements are taken to sufficient depths. Depth measurements for outwash will reveal a decreased resistivity when the till is encountered, whereas the resistivity of bedrock with shallow overburden continues to increase in an almost linear manner up to the maximum electrode separation (because the thickness of the bedrock is usually very much greater than the maximum electrode separation).*

Under some conditions, it is difficult to distinguish between the two deposits. For example, outwash overlying bedrock could easily be misinterpreted as bedrock since the actual resistivity of the two might be of the same order of magnitude, and the contact between the two might be detected. Two such curves were obtained in the Big Sioux outwash valley in Minnehaha County, South Dakota. One of these (shown in Figure V) was taken within a half mile of a Sioux Quartzite outcrop near Baltic, South Dakota. Both curves are believed to bottom in quartzite but no drill log was available to substantiate this belief.

In a few cases, the resistivity curves appear to indicate outwash over bedrock with a layer of till between, as shown in Figure V. For this curve, the increasing resistivity in the first 20 feet is

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*It should be understood that this argument may not hold true for all types of bedrock; only for those having a high resistivity.

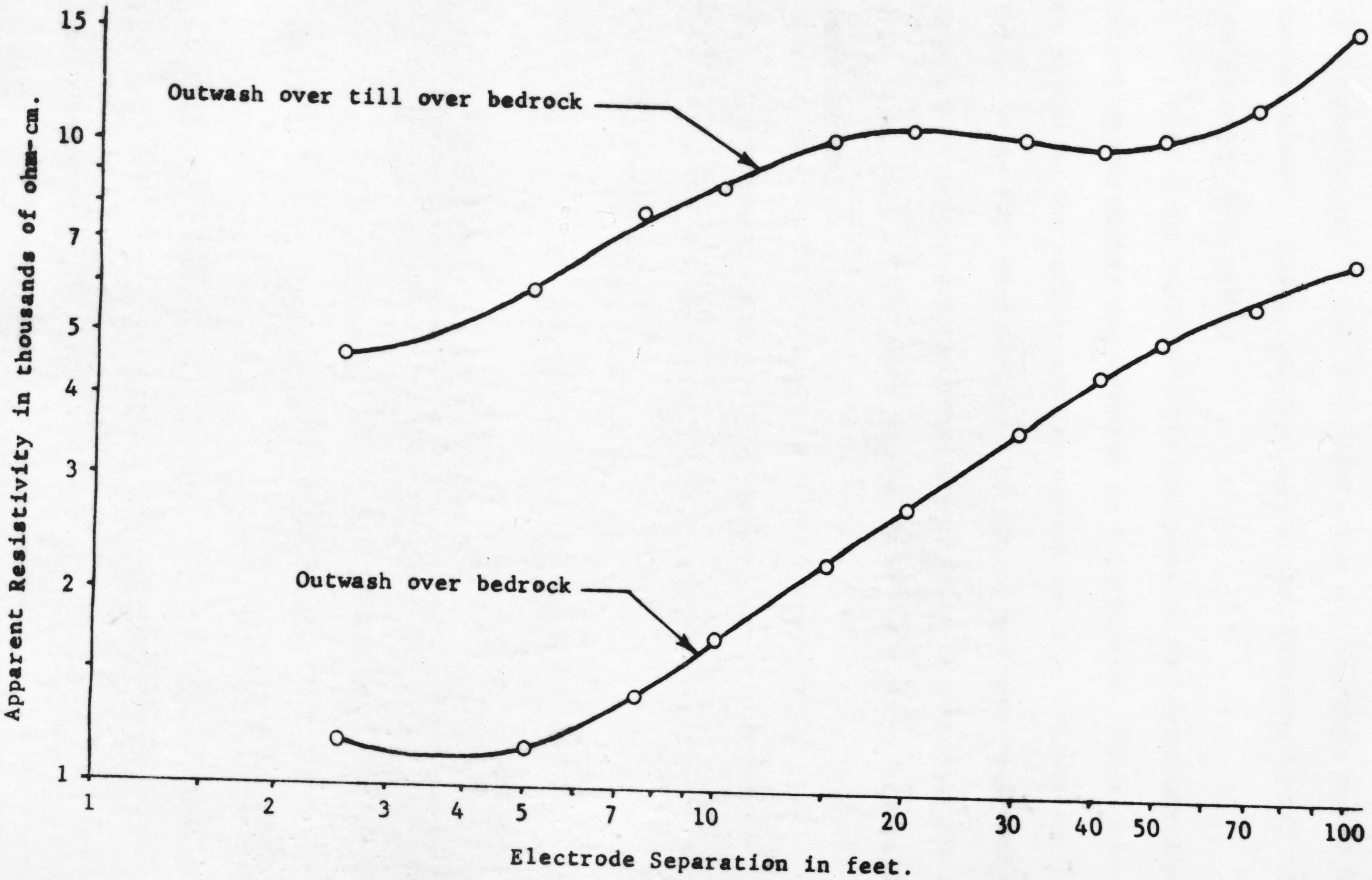

Figure V. Outwash over bedrock resistivity curves.

caused by the outwash, the decreasing resistivity between 20 and 40 feet is apparently due to the till layer, and the increase beyond 40 feet is due to bedrock. Again, no drill log is available to verify the interpretation of this curve.

Only a few representative examples of the very extensive data obtained by the author are included in this thesis. These data are shown as points on the various graphs, and in one case (Figure IX) in tabular form. It is felt that inclusion of all of the data would only make the thesis more cumbersome and would add nothing to clarity. The complete data is on file at the South Dakota State Geological Survey, Vermillion, South Dakota.

INTERPRETATION OF RESISTIVITY MEASUREMENTS

As previously stated, the shape of the field curve can be used to determine the general nature of the underlying beds. More detailed information is usually required, however, and the interpretation must specify the thickness and nature of overburden, the depth to contacts, and the nature of each of the underlying beds. Such an extensive interpretation is not a simple process, and numerous articles have been published regarding methods of interpretation. These methods fall into two general categories: 1) emperical methods, and 2) theoretical methods. The emperical methods have no theoretical basis and are used because they give satisfactory results (under certain conditions) and they are generally quite easy to apply. The theoretical methods are usually more difficult to apply, and under favorable conditions will give good results.

Emperical Methods of Interpretation

Gish-Rooney method

One of the first, and probably the most easily applied, methods of emperical interpretation is credited to Gish and Rooney (4). In using this method, a change in the slope of the field curve is considered to indicate the contact between beds of differing resistivity; the depth to the contact is roughly equal to the electrode separation at which the change in the field curve occurs. The basis for this interpretation lies in the assumption that the equipotential surfaces are bowl shaped (hemispherical) and are symmetric about the current electrodes. In this case, the electrode separation would be equal to the maximum depth of the "potential bowl" and as such would indicate the maximum depth for which the layer below the contact would have no influence on the measured resistivity. Since the earth is seldom homogeneous, the contacts are not plane and frequently dip, and the layers have different values of resistivity, the equipotential surface will be distorted from the symmetric bowl shape and the electrode separation is at best a rough indication of the maximum depth being measured.

<u>Moore's cumulative method</u>

Another emperical method of interpretation was developed by Moore (13) in which the cumulative sum of the resistivities is plotted against electrode separation. "The initial value of apparent resistivity is plotted as the initial ordinate of the cumulative curve. Each subsequent value of apparent resistivity is added to the sum of all preceding resistivity values and each total thus obtained is plotted as the ordinate of another point on the cumulative curve." (13) The electrode separation at which the lines (drawn tangent to the cumulative plot) intersect is taken as the approximate depth to the contact. According to Moore, the cumulative plot minimizes the effect of variation in the resistivity data due to local irregularities in the surface and subsurface layers, and due to the inaccuracies of taking the measurements. This is because a greatly reduced scale is required to plot the cumulative sum of the resistivities.

<u>Linear plot of field data</u>

During the study of a report by Lum (8) in which resistivity measurements taken along the Big Sioux River in eastern South Dakota were interpreted, it was noted by the author that contacts could frequently be predicted from the field curve. When plotted on log-log paper, the field curve consists of several connecting curve segments. If each segment is considered to represent one subsurface layer, the contacts occur approximately at a depth corresponding to the electrode separation at the midpoints of the segments. This is illustrated in Figure VI. In practice, it is difficult to determine the inflection points on the log-log curve; but if the field curve is plotted on linear graph paper many of the segments are transformed into straight lines whose midpoints can readily be determined. The midpoint of the segment on the log-log curve of Figure VI can be expressed as;

$$\log C = \frac{1}{2} (\log X_1 + \log X_2) \quad \text{from which } C = (X_1 X_2)^{\frac{1}{2}}$$

is the midpoint of the log-log curve when plotted on linear paper.

The problem of determining the nature of the different beds is difficult, but it can be accomplished by initially comparing resistivity curves to drill logs. This will provide a reference on which to base the interpretations for a given area.

This method of interpretation requires that curved portions of the plotted field data be approximated by straight lines, making interpretations unreliable when such field curves are encountered.

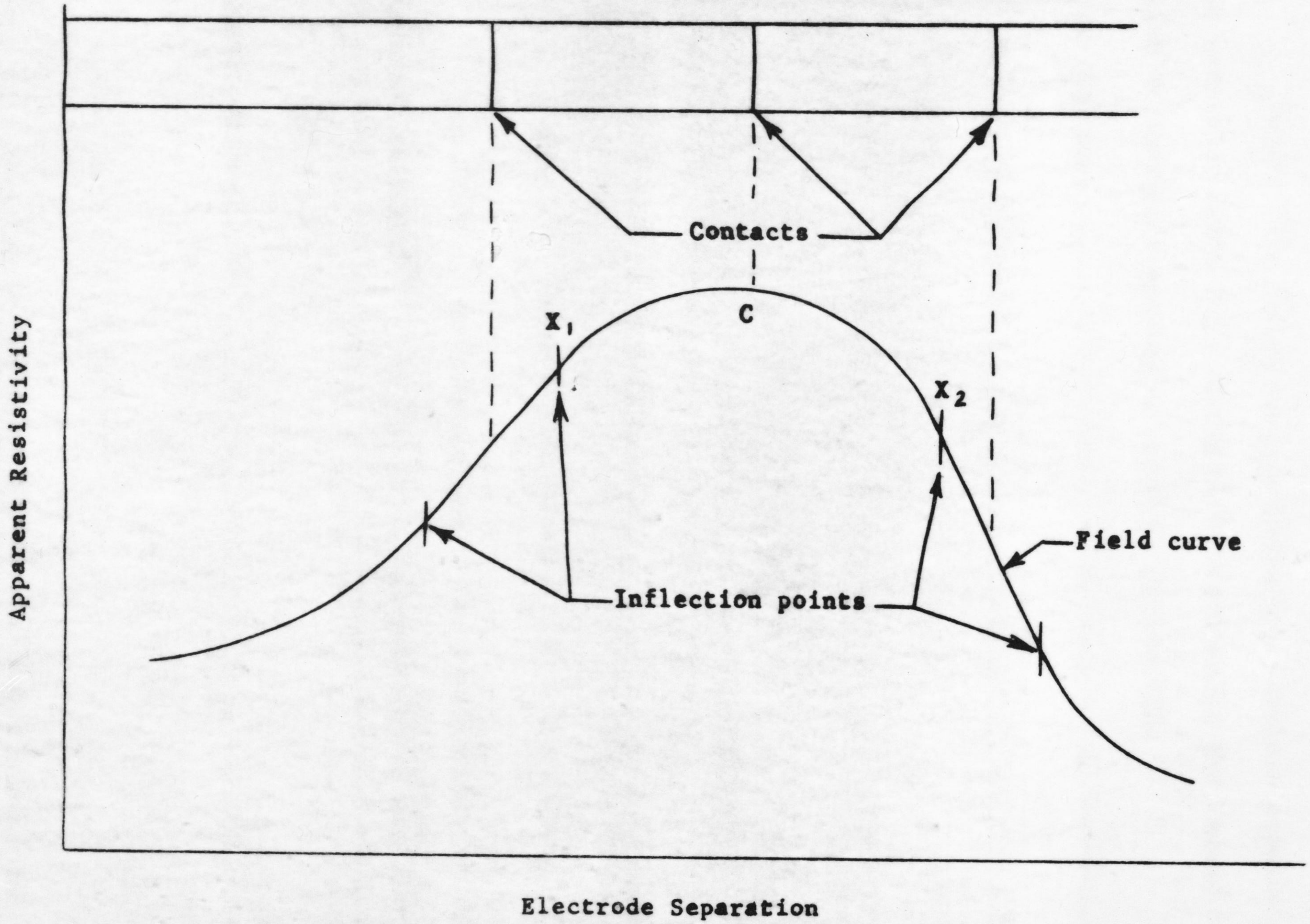

Figure VI. Method for determining contacts from field curve.

Theoretical Methods of Interpretation

Tagg's method

Tagg's (16) method of interpretation involves equations derived by Lancaster Jones for a two layered earth using the Wenner configuration of electrode spacing as shown in Figure VII.

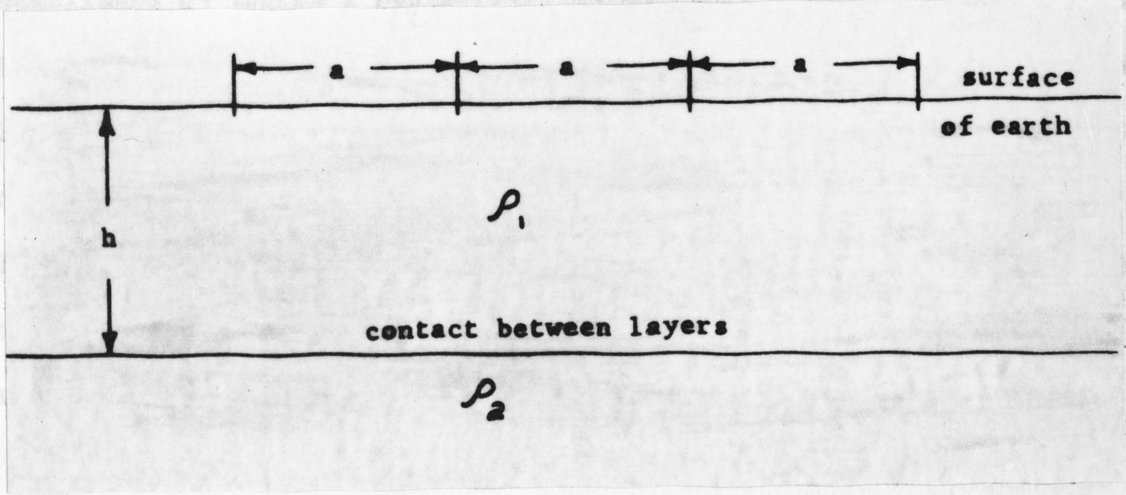

Figure VII. Wenner configuration for a two layered earth.

The first of these equations is the relationship of the measured apparent resistivity ρ_a to the actual resistivity of the first layer ρ_1.

$$\frac{\rho_a}{\rho_1} = (1 + 4F)$$

where $$F = \sum_{n=1}^{n=\infty} \left[\frac{K^n}{\sqrt{1 + \left(2n\frac{h}{a}\right)^2}} - \frac{K^n}{\sqrt{4 + \left(2n\frac{h}{a}\right)^2}} \right]$$

and $K = (\rho_2 - \rho_1) / (\rho_2 + \rho_1) = (1 - \frac{\rho_1}{\rho_2}) / (1 + \frac{\rho_1}{\rho_2})$,

or K is a function of the ratio of the two resistivities and may have any value between -1 and +1.

Tagg master curves (16), as they are called, are a family of curves of $\frac{\rho_a}{\rho_1}$ versus h/a, with each curve representing an assumed value of K.

Before an interpretation can be made using the Tagg master curves, the value of ρ_1 must be experimentally determined. This is accomplished by taking a resistivity measurement with a very small electrode separation (on the order of one foot) so that only the upper layer influences the measured resistivity. In taking this measurement, the electrodes must not be pushed too deeply into the earth or they will no longer act as point sources and the value obtained for ρ_1 will not be correct. In general, several readings should be taken and the recorded values averaged to obtain the best value for ρ_1.

In applying Tagg's method of interpretation, a value of ρ_a (with a corresponding value of a) is selected from the field data and the value for $\frac{\rho_a}{\rho_1}$ is determined. For this value of $\frac{\rho_a}{\rho_1}$, several values of K and the corresponding values of h/a are determined from the master curve. These are plotted as a curve of K versus h (h can be determined because a is known). Other values of ρ_a and a are selected and the procedure is repeated with all K versus h curves plotted on the same graph. Under ideal conditions, all curves will intersect at a point corresponding to the depth to the contact (h), but in practice, they do not because conditions deviate from the ideal. However, if the intersections occur over a small area, the depth to the contact can be determined to some degree of accuracy.

Mooney-Wetzel master curves

Mooney and Wetzel (12) have published a large number of theoretical earth-resistivity curves which can be used for interpretation of field curves. The theory of images is used in computing the curves and assumptions are made that each layer is electrically homogeneous and that the contacts between layers, as well as the earth surface, are horizontal plane surfaces. Each curve represents a set of assumed values of resistivity for each layer and for depth to the various contacts between layers. The curves are plotted on log-log paper with relative depth as abscissa and relative resistivity as ordinate and as such are independent of units of depth and resistivity.

Field curves are plotted as log-log curves to the same logarithmic scale as the theoretical curves. When a theoretical curve can be found that matches the field curve, the interpretation is simply a matter of reading the value of resistivity of the top layer and the depth to the bottom contact from reference lines on the theoretical curve. The assumed relationships between the various depths and layer resistivities of the theoretical curve can then be used to determine the remaining values of resistivity and depth to contacts.

DISCUSSION OF THE METHODS OF INTERPRETATION

During the summer of 1957, sample logged drill holes were drilled in Codington and Hamlin Counties of South Dakota. The drill logs, and their locations, were included in a report by Steece (15). Resistivity stations were set up during the summer of 1962 by the author at 38 of the above mentioned locations in order that resistivity interpretations could be evaluated by a comparison with the drill logs.

Linear Plot of Field Data

Data from the 38 resistivity stations were interpreted from a linear plot of the field data as previously described. Three of the curves were correctly identified as till. Of the remaining 35 outwash curves, the agreement between the resistivity interpretation and the drill log is shown in Table 2. Agreement was based on: (1) proper location of the contacts between layers, and (2) correct identification of each layer. Each of the criteria was given equal weight in determining if agreement was good, fair, or poor.

Table 2. Agreement between reisitivity interpretation and drill log

	Agreement					
	Good	Fair to Good	Fair	Fair to Poor	Poor	Very Poor
Number of Curves	7	2	6	7	11	2

It would appear from Table 2 that this method of interpretation has little merit; however, the conditions under which the resistivity measurements were taken must be considered. Hand auger holes were dug to a depth of 5 feet at each resistivity station, and the results were recorded. At many locations, the agreement between the hand auger logs and the upper part of the drill logs was very poor. It was usually impossible to take the resistivity readings at the same location as the drill hole because the drill holes were generally drilled in road ditches at section corners, and the resistivity stations had to be located several hundred feet away. Changes in overburden, as well as in the depth to, and thickness of, underlying beds would be expected under these conditions.

If there is poor agreement between the drill and hand auger logs for both thickness of overburden and the type of material lying below the overburden, it is highly probable that the resistivity interpretation will not agree with the drill log. A tabulation (Table I)* was made of agreement between hand auger log and the upper part of the drill log, along with agreement between resistivity interpretation and drill log.

From this tabulation, it is possible to determine the correlation between resistivity interpretation and the agreement between drill and hand auger logs. The results of this correlation are shown in Table 3.

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*See Appendix B

Table 3. Correlation of resistivity interpretation and the agreement between hand auger log and drill log

	Correlation					
	Good	Fair to Good	Fair	Fair to Poor	Poor	Very Poor
Number of Stations*	11	6	3	2	5	0

*Eight stations are not included in this table because of inconclusive agreement between hand auger log and drill log.

With 20 stations having a fair or better correlation, and only seven with less than fair, it appears that most of the poor agreement between resistivity interpretation and drill logs shown in Table 2 is caused by actual differences in underlying materials. From this, we should expect good interpretations only when there is good agreement between hand auger log and drill log.

Figure VIII compares the resistivity interpretation with the drill log at one of the seven locations where there was fairly good agreement between the hand auger log and the upper part of the drill log. Although most of these seven interpretations agreed quite well with the drill logs (with the exception of the first contact), it is not a sufficient number to produce a reliable evaluation of this method of interpretation. It is possible, and quite probable, that this method will give correct interpretations only for certain combinations of layered earth. For a proper evaluation, it would be necessary to take a number of resistivity readings under more closely controlled conditions with drill hole and resistivity station at identical locations.

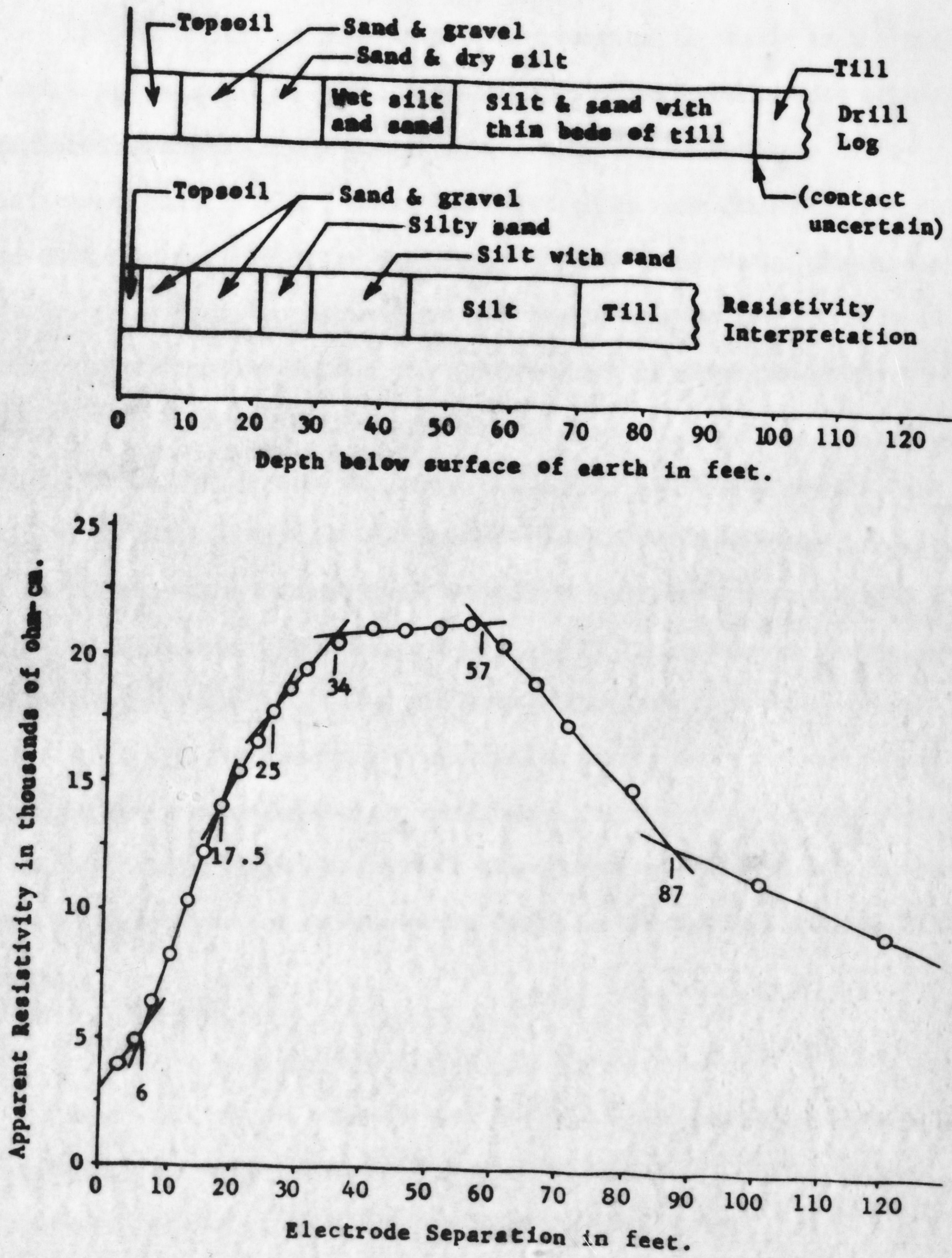


Figure VIII. Interpretation of field curve using linear plot of field data, for Station No. 3.

Gish-Rooney Method

In this method of emperical interpretation, a change in the slope of the field curve is taken to represent a contact between beds of differing resistivity. Field curves obtained by the author were interpreted using this method. These interpretations were generally not as good as those obtained using the linear plot of field data. It should be noted that these two methods are not consistent, as one predicts contacts at the midpoints between the intersection of lines while the other predicts them at the intersection.

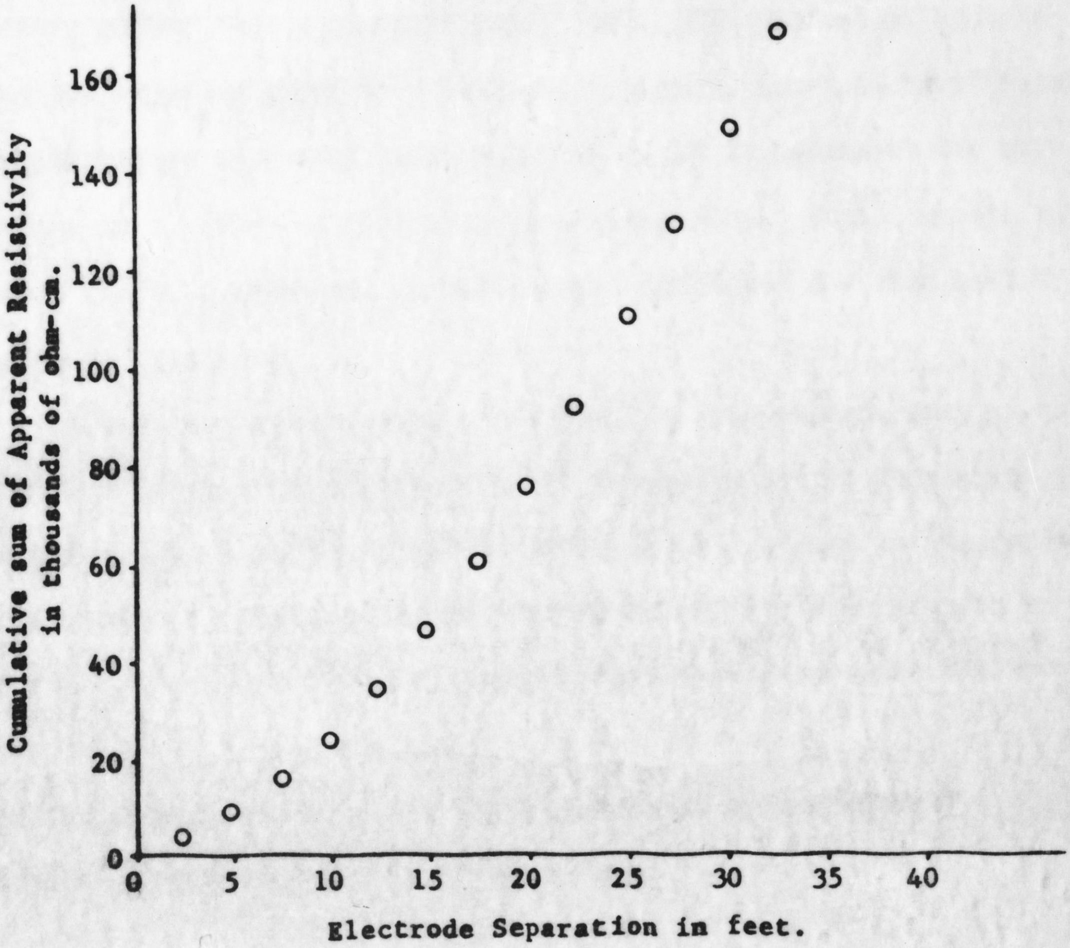
For the field curve of Figure VIII, the Gish-Rooney method does not predict the contacts as well as does the author's method.

In commenting on emperical methods of interpretation, Heiland (5) makes the statement: "The apparent resistivity continues to change with electrode separation long after the true resistivities have ceased to change with depth." Model tank experiments conducted by Manhart (9) also show that, under laboratory conditions, there are no abrupt changes in the resistivity curve, and that a point where a change in slope occurs does not generally correspond to depth to the contact between layers.

Moore's Cumulative Method

Cumulative curves were plotted for all the field data obtained by the author. The curve shown in Figure IX is typical of those plotted for outwash readings. Note the smoothness of the curve.

When several layers of earth are involved, the cumulative curves are frequently in "the form of a generally smooth curve of gentle



Electrode spacing (feet)	Resistivity (ohm-cm)	Cumulative sum (ohm-cm)
2.5	3,930	3,930
5.0	4,890	8,820
7.5	6,420	15,240
10.0	8,200	23,440
12.5	10,300	33,740
15.0	12,200	45,940
17.5	14,000	59,940
20.0	15,400	75,340
22.5	16,600	91,940
25.0	17,800	109,740
27.5	18,700	128,440
30.0	19,500	147,940
32.5	20,300	168,240

Figure IX. Plot of cumulative resistivity for Station No. 3.

curvature rather than a straight line" (13). The process of approximating this type of curve by a series of straight lines is very inexact as any number of different lines might be drawn to represent the curve, resulting in a number of different interpretations. When a smooth cumulative curve is obtained, as illustrated in Figure IX, this method fails to give results.

It has been pointed out by Heiland (5), and others, that an abrupt change in the resistivity curve is necessary if the cumulative is to be other than a smooth curve, and that abrupt changes in the resistivity curve are generally due to variations in electrode contact resistance. This means that, in general, the cumulative curve will be smooth, and when a definite change in slope does occur, it is usually caused by errors entering into the measurements rather than by a contact between beds of differing resistivity.

Tagg's Method

Tagg's method was used to interpret a few selected curves with poor results. The curves obtained intersected over such a wide area that it was impossible to determine contacts to any degree of accuracy. This method is very time consuming because data necessary to plot the several curves (whose intersection determines the depth to the contact) must be graphically determined from the master curve for several different values of resistivity. Also, certain combinations of bed thickness and resistivity ratios are very difficult to interpret and in some cases result in very inaccurate solutions or no solution at all (7).

Tagg's method is not recommended for interpretation of outwash resistivity curves because it will only determine the first contact, and this contact can be found directly by drilling a 5 foot hand auger hole, provided the overburden is 5 feet or less.

Mooney-Wetzel Master Curves

Theoretical curves representing approximately 2400 different resistivity and depth ratios were used in an attempt to match the field curves to a theoretical curve.

In using the theoretical curves, it is essential that the interpreter know the general shape of the theoretical curve which represents a particular resistivity ratio, so that only a small number of the theoretical curves need be compared to the field curve. The resistivity ratio is the ratio of the various layer resistivities to the resistivity of the first layer. (The ratio 1:3:10:1/3 indicates a second layer with three times the resistivity of the first, a third layer with ten times the resistivity of the first layer, etc.) For the Mooney-Wetzel master curves ten different depth ratios are plotted for each resistivity ratio, so the curves represent a large number of different layer conditions.

An experienced interpreter might predict a curve match between the outwash curve of Figure III and a theoretical curve of resistivity ratio of 1:3:10:1/3 or 1:10:1 because experience tells him that these theoretical curves have a shape similar to the outwash curve. He would not attempt to match the outwash curve with theoretical curves of resistivity ratios 1:100:10, 1:1/3:10 or 1:1/10:1 because these curves are known to have shapes far different from the field curve.

Figure X compares the outwash curve of Figure III to the theoretical curve of resistivity ratio 1:3:10:1/3 and depth ratio 1:2:6. This is a reasonably good match between 5 and 60 feet. The reference lines of the master curve coincide with 1,050 ohm-cm and 28 feet of the outwash curve and predict the resistivity of the first layer (R_1) to be 1,050 ohm-cm and the depth to the third contact (D_3) to be 28 feet. Using the resistivity ratios, the resistivity of the second layer is 3,150 ohm-cm, of the third layer 105,000 ohm-cm, and of the fourth layer 350 ohm-cm. From the depth ratio, the first contact is at 4.67 feet and the second contact at 9.34 feet.

This interpretation indicates a sand and gravel layer (105,000 ohm-cm) between 9.34 feet and 28 feet while the drill log for this station (No. 32) shows sand and gravel between 10 feet and 60 feet. It will be noted from Table I, that the hand auger log and drill log agreement is inconclusive, and from Figure X, that the curve match is not good for the small and the large electrode separations, thus we should not be surprised that the agreement between the theoretical curve interpretation and the drill log is not good.

Even with the numerous theoretical curves available, the author found only six field curves, of the 38, which could be matched to a reasonable degree of accuracy. This points out the main disadvantage of the theoretical curves. At present, they are only available for two, three and four layers of earth, and for a limited number of layer conditions. In practice, five or more layers are frequently encountered

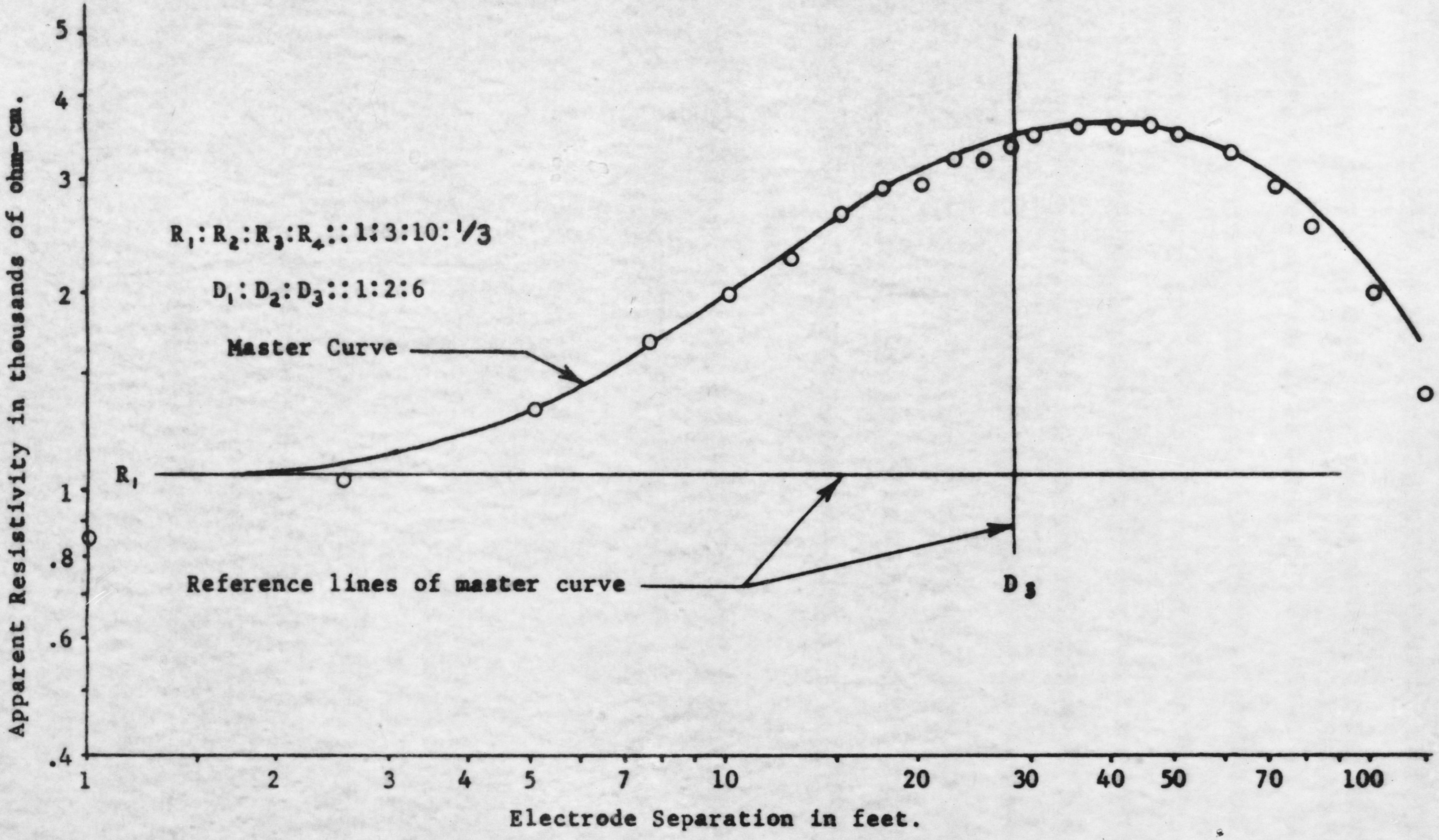


Figure X. Outwash curve of Figure III matched to master curve.

and an infinite number of layer conditions can exist. Therefore, a field curve can rarely be made to match completely a calculated curve (11). Another reason why the field curve may not match the theoretical curve is that the assumed conditions of homogeneous layers and plane contacts between layers are often not satisfied in the field.

Interpolation can sometimes be used when the field curve does not match one of the master curves, but the reliability of such interpolation depends to a large degree on the skill of the interpreter. However, a familiarity with the master curves will give the interpreter a feel for the behavior of the resistivity curves under various conditions (11), and this is an invaluable tool that has applications in all methods of interpretation.

When a master curve can be found that matches the field curve, the interpretation is simple and quite reliable.

SUMMARY OF RESISTIVITY INTERPRETATIONS

For earth-resistivity data to be interpreted reliably, it is necessary that the interpreter have a thorough knowledge of the earth-resistivity method, of the general geology of the area under investigation, and that he be thoroughly familiar with as many different methods of interpretation as possible (14).

The emperical methods of interpretation are often of great value because of their simplicity of application. In an area where the results are shown to be generally reliable, the fact that these methods have no theoretical basis should be no cause for concern. Interpretation using the linear plot of field data shows promise of being an effective method of interpretation, but further investigations are needed before any realistic evaluation of this method can be made. While the theoretical methods would seem to be generally more reliable, their usefulness depends on how nearly the geologic conditions of the earth match the assumed conditions used in deriving the theoretical curves.

Of the various theoretical methods, curve matching with the Mooney-Wetzel master curves is probably the most useful, because an interpreter familiar with the curves can make a qualitative interpretation even when the match between the field curve and the theoretical curve is poor. A knowledge of the master curves is also helpful when interpretation is done by other methods.

Sample logged drill holes should be used as an initial reference on which to evaluate interpretations by different methods. It may be found that one method of interpretation gives reliable predictions of subsurface layers in one area, but not in another, so the interpreter should not rely on one method.

It should be pointed out that it is virtually impossible to devise any means of resistivity measurements and interpretations that will always agree with the drill log. If the contact between lithologic layers is very irregular, the resistivity interpretation will specify the average lithology over a rather large distance, while the drill log will determine the lithology at a given point (17), and the two may or may not agree. When extremely poor agreement between resistivity interpretations and drill log is encountered, more drill logs should be obtained in the immediate area to be certain that the drill log actually is representative of the average lithology. Only when this is done can the resistivity interpretation be correctly evaluated.

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APPENDIX A

Definitions of Geologic Terms as Used in This Report

(listed in order of first occurance in text)

1. Till .... A stiff clay full of stones varying in size up to boulders (also called "moraine" or "boulder clay").
2. Drill log .... A tabulation of materials and the depths below the surface at which they are located, as determined from drilling down into the earth with some type of powered drill and sampling the materials at frequent intervals of depth.
3. Outwash .... Layers of sand and gravel deposited by the melt-waters of a glacier.
4. Alluvium .... Sediments laid down in river beds, flood plains and lakes in comparatively recent times.
5. Loess .... A homogeneous, nonstratified (not deposited in layers) sediment composed predominantly of silt with subordinate amounts of very fine sand and clay, deposited primarily by the wind.
6. Kames .... Hills or ridges of stratified sand and gravel, formed in contact with glacier ice.
7. Kame Terrace ...... A terrace like body of stratified sand and gravel deposited between a glacier and an adjacent valley wall.
8. Bedrock .... Any solid rock underlying soil, sand, clay, etc.
9. Overburden .... Material of any nature which overlies the particular deposit under investigation.
10. Sioux Quartzite ... The bedrock underlying a part of eastern South Dakota.
11. Outcrop .... To crop out; to come out to the surface of the ground.
12. Hand auger log .... Similar to a drill log except that a hand auger is used rather than a powered drill.

APPENDIX B

Table I. Agreement between hand auger log and drill log, and between resistivity interpretation and drill log

Station	Hand auger and drill log agreement: overburden	Hand auger and drill log agreement: material	Agreement between resistivity interpretation and drill log
1	fair-poor	fair	poor
2	poor	fair	good
3	good	fair	good
4	good	good	good
5	poor	poor	fair-poor
6	fair-good	good	fair-good
7	poor	*	good
8	poor	fair	fair-poor
9	fair	good	fair
10	fair-good	fair	poor
11	fair-poor	fair-poor	fair
12	poor	good	fair
13	fair-poor	good	fair-good
14	poor	fair	fair-poor
15	fair	poor	poor
16	poor	fair	poor
17	very poor	very poor	poor
18	fair-good	fair	fair-poor
19	fair	good	poor
20	*	*	poor
21	fair-good	fair-good	very poor
22	fair-poor	fair	good
23	good	fair	good
24	none	none	poor
25	*	*	fair
26	*	*	fair-poor
27	*	*	poor
28	*	*	poor
29	poor	fair-good	fair-poor
30	very poor	fair	very poor
31	good	good	fair
32	*	*	fair
33	fair-poor	fair	fair-poor
34	*	*	good
35	poor	poor	poor

*Inconclusive agreement